

DYNAMIC MAGNETIZATION OF METALLIC GLASSES

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Dynamic magnetization measurements have been made on toroids of several commercially available ferromagnetic metallic glasses. Constant dB/dt excitation was used for times-to-saturation as short as 300 ns. Magnetic losses and maximum pulse permeabilities calculated from these measurements are reported. The effects of ribbon thickness and insulation on these properties are discussed.

Introduction

The response of ferromagnetic metallic glasses to fast pulse magnetization has resulted in their use as ferromagnetic core materials, both in saturable inductors for pulse compression, and in inductors to couple energy into charged particle beams. Performance of devices using metallic glasses has been reported at this conference in previous years [1-3] and has been summarized elsewhere [4]. The important magnetic properties for designing such devices are the achievable change in induction, unsaturated and saturated permeabilities, and magnetic losses at the desired magnetization rates. The change in induction determines the amount of material required in a device. The ratio of unsaturated to saturated permeabilities determines the maximum pulse compression per stage and the efficiency. The magnetic losses also affect the efficiency and the maximum repetition rate.

Magnetic losses in ferromagnetic ribbons under fast magnetization are often described in terms of a simple saturation wave model of magnetization. In this model eddy currents circulate around a collapsing domain magnetized in the original direction. The calculated magnetic losses depend only on the ribbon thickness, resistivity, saturation induction, and the rate of magnetization. In thin metallic glasses, however, this simple behavior is not observed at magnetization rates up to 3 T/ μ s [5]. Also, the losses do not increase as predicted with the square of the thickness.

The experiments described in this paper were intended to extend the data base of dynamic magnetization characteristics for a variety of commercially available metallic glasses. Magnetization rates have been extended to approximately 10 T/ μ s. Results are reported for a variety of thicknesses between 14 and 30 μ m and for unannealed as well as annealed ribbons. Measurements on uninsulated ribbon demonstrate the importance of insulation in measurement of dynamic magnetization of metallic glasses.

Theory

Models of domain wall motion in ferromagnetic metallic glass ribbons have been described elsewhere [5-9]. They are very similar to those developed earlier for crystalline magnetic alloys. However, most attention has been paid to the simple saturation wave model which is tractable to easy calculations. The H-field required to magnetize a ribbon of thickness d , resistivity ρ , and saturation induction B_s is:

$$H_{sw} = H_c + (d^2/4\rho) (\Delta B/2B_s) (dB/dt). \quad (A/m) \quad (1)$$

The dc coercive force is H_c and ΔB is the change in induction, usually measured from negative remanence. This equation is integrated to give the saturation wave losses to any value of ΔB . This value corresponds to the area between the dynamic magnetization curve and the B axis.

$$E_{sw} = H_0 \Delta B + (d^2/8\rho) (\Delta B^2/2B_s) (dB/dt) \quad (J/m^3) \quad (2)$$

These equations predict that the drive field will increase linearly with ΔB until saturation. This behavior represents a constant permeability. The permeability can be calculated by ignoring the coercive force and taking the ratio of $\Delta B/H$.

$$\mu = (8\rho B_s/d^2) (dB/dt)^{-1} \quad (H/m) \quad (3)$$

The MKS unit for permeability, henries per meter, can be converted to dimensionless relative permeability by dividing by the MKS permeability of free space.

At lower magnetization rates, a much different behavior is seen. At extremely low magnetization rates, widely spaced, ribbon-spanning bar domains result in a drive field which is constant with ΔB . While the dependence on dB/dt is the same as that for the saturation wave model, the required H increases linearly with thickness instead of as thickness squared. In addition the domain wall spacing $2L$ appears in the equation [10].

$$H_{bd} = H_c + 0.54 (d^2/4\rho) (2L/d) (dB/dt) \quad (A/m) \quad (4)$$

Terms have been arranged for easy comparison to (1). Note that the drive field does not depend on ΔB . Since $2L/d$ is large for widely spaced walls, the drive field will be larger than for saturation wave behavior. The losses are again obtained by integrating equation [4]. The bar domain losses depend linearly on dB/dt as did the saturation wave losses. However, the thickness dependence is first rather than second power.

$$E_{bd} = H_c \Delta B + 0.54 (d^2/4\rho) (2L\Delta B/d) (dB/dt) \quad (A/m) \quad (5)$$

In the transition region between these limiting cases, the domain wall configuration is the result of a balance between magnetizing pressure, domain wall energy, and bowing of the domain walls [11,12]. The bowing of domain walls causes increased domain wall area. Therefore, the eddy currents around the domain walls are distributed over a wider volume. The drive field is lower than that for bar domains but higher than that for a saturation wave domain. Experimental evidence shows a dependence of the drive field on the square root of dB/dt [13].

Experimental Procedures

Melt-spun ribbons of several commercially available metallic glass alloys were obtained from Metglas Products in Parsippany, NJ. The compositions and nominal properties of the ribbons are given in Table I. Their mean thicknesses were calculated from sample weights of one meter lengths. Ribbons were coated by passing them through a bath containing

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Table I. PROPERTIES OF ALLOYS USED IN THIS EXPERIMENT

Alloy Designation	Nominal Composition (At.%)	Density g/cm ³	Resistivity $\mu\Omega\text{m}$	Curie Temperature $^{\circ}\text{C}$	Saturation Induction T	Field Anneal Conditions
METGLAS® Alloy 2605CO	Fe ₆₇ Co ₁₈ B ₁₄ Si ₁	7.56	1.30	415	1.80	325°C, 2hrs. 1600 A/m
METGLAS Alloy 2605SC	Fe ₈₁ B _{13.5} Si _{3.5} C ₂	7.32	1.25	370	1.61	365°C, 2hrs. 800 A/m
METGLAS Alloy 2605S-2	Fe ₇₈ B ₁₃ Si ₉	7.18	1.30	415	1.56	380°C, 2hrs. 800 A/m
METGLAS Alloy 2826MB	Fe ₄₀ Ni ₃₈ Mo ₄ B ₁₈	8.02	1.60	355	0.88	355°C, 2hrs. 800 A/m
METGLAS Alloy 2705M	Co ₆₉ Fe ₄ Ni ₁ Mo ₂ B ₁₂ Si ₁₂	7.8	1.0	330	0.7	380°C, 0.5hrs. 800 A/m

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colloidal silica particles (average size 15 nm) in isopropanol and drying the coating with hot air. This procedure resulted in the formation of tenacious films approximately 200–600 nm thick, as measured by Auger spectroscopy, on top and bottom surfaces. Toroids of 13 cm mean length containing 10 g of 25 mm or 50 mm width ribbon were wound on ceramic bobbins and annealed in an inert atmosphere. Annealing conditions are given in Table I where field condition refers to a circumferential field. DC B-H loops were measured to 80 A/m using a Magnos hysteresigraph. For dynamic magnetization measurements, the toroids were driven by discharging a low inductance capacitor bank through 3 or 10 turns of 18 gage wire wound through the toroid. The current in the primary coil was measured using a Tektronix P6021 current probe. A one turn secondary provided a voltage proportional to dB/dt. The secondary winding encircled only core material to minimize its area and pick-up of dB/dt in air. A separate winding was used to supply a reset field before magnetization to allow maximum ΔB from negative remanence to saturation. Voltage and current waveforms were digitized at 20 nsec/pt and recorded by a Nicolet 4094 oscilloscope. A microprocessor in the oscilloscope allowed post-processing of the data including integrating, scaling, and multiplication provide direct readings of ΔB , H, and energy in J/m³.

Results

The toroids prepared from various thickness samples of several alloys are summarized in Table II. Annealing, insulation, and thickness are listed as well as the dc properties and typical ΔB under pulsed magnetization. Insulated and annealed toroids were made from all available ribbon thicknesses. Uninsulated toroids and insulated but unannealed toroids were made from the ribbons closest to 25 μm for each alloy.

The losses measured for ribbons closest to nominal 25 μm thickness are shown in Figure 1 as a function of magnetization rate. Average ΔB is given for each toroid. The losses increase as dB/dt to the 0.85 power. These magnetization rates are apparently below the onset of saturation wave behavior. It is clear that the alloys have not only differing ΔB 's, but also differing losses in this range of dB/dt. METGLAS Alloy 2605CO with the largest ΔB had the highest losses while METGLAS Alloy 2705M with the smallest ΔB had the lowest losses. To compensate for differing values of ΔB , the measured values of average excess drive field are shown in figure 2 for the same toroids. Excess H has been calculated by dividing by ΔB and subtracting the dc coercive field. The alloys show the same ordering with METGLAS Alloy 2605CO exhibiting the highest drive field and METGLAS Alloy 2705M the lowest. The difference in losses, therefore, are

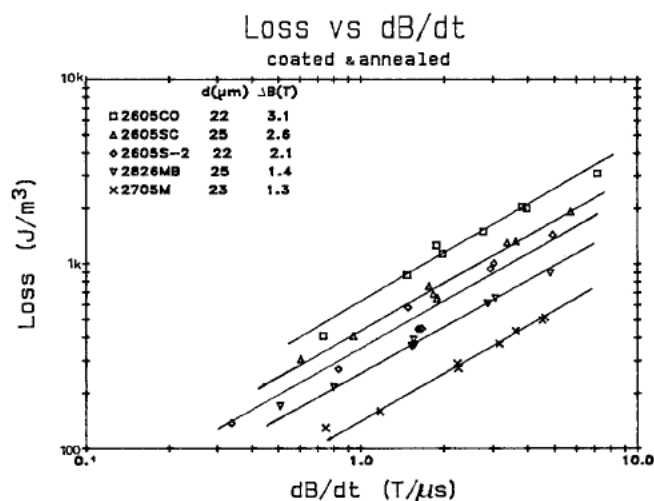


Figure 1. Magnetic losses as a function of dB/dt for several alloys of nominal thickness.

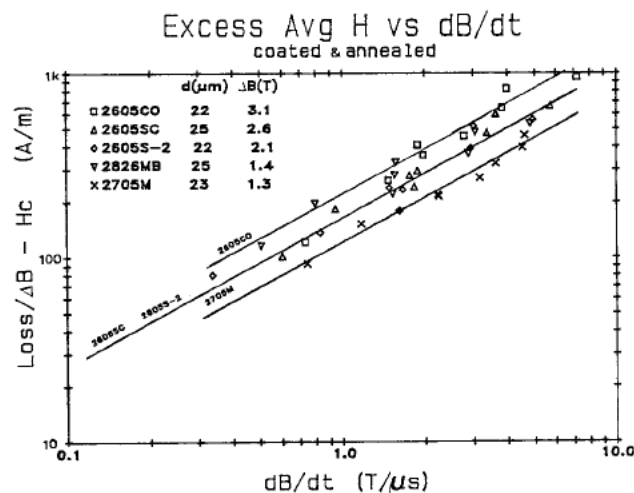


Figure 2. Average excess drive fields as a function of dB/dt for several alloys of nominal thickness.

Table II. DC Properties of Toroids Measured. 'I' indicates insulated. 'A' indicates annealed.

METGLAS Alloy	Thickness (μm)	H_c (A/m)	B_r (T)	B_{80} (T)	ΔB (pulse) (T)
2605CO IA	30	5.8	1.61	1.7	3.3
2605CO IA	22	2.4	1.62	1.66	3.12
2605CO IA	16	2.2	1.60	1.68	3.17
2605CO IA	14	6.8	1.67	1.69	3.32
2605CO I	22	5.0	0.88	0.99	1.97
2605CO A	22	2.7	1.64	1.67	3.37
2605SC IA	25	3.3	1.38	1.41	2.57
2605SC IA	22	2.4	1.44	1.51	2.62
2605SC IA	19	2.2	1.31	1.50	2.27
2605SC IA	14	5.2	1.29	1.49	2.52
2605SC I	25	5.4	0.80	0.87	1.78
2605SC A	25	2.2	1.40	1.51	2.74
2605S-2 IA	30	2.6	1.11	1.43	2.76
2605S-2 IA	22	5.0	1.11	1.32	2.14
2605S-2 IA	20	1.5	1.36	1.47	2.75
2605S-2 IA	19	1.6	1.31	1.56	2.64
2605S-2 I	22	12.8	0.46	0.63	1.44
2605S-2 A	22	1.6	1.13	1.37	2.37
2826MB IA	25	0.8	0.81	0.90	1.42
2826MB I	25	3.2	0.36	0.43	0.94
2705M IA	23	0.8	0.68	0.72	1.26
2705M I	23	1.0	0.61	0.70	1.28

not simply due to differences in ΔB . Domain configurations within the ribbons during magnetization also have an influence.

Similar measurements of losses for unannealed toroids of the same ribbons are shown in Figure 3. The actual values of the losses are somewhat lower than for annealed ribbons because the values of ΔB achieved are much lower--typically 60-70%. The exception is METGLAS Alloy 2705M which is a near-zero magnetostriction alloy. This alloy is relatively stress insensitive. Annealing relieves winding stresses.

Variations of losses with ribbon thickness are shown in Figures 4 and 5 for METGLAS alloys 2605CO and 2605SC respectively. The intercepts of loss vs. dB/dt at 10 T/ μs plotted against thickness on a log-

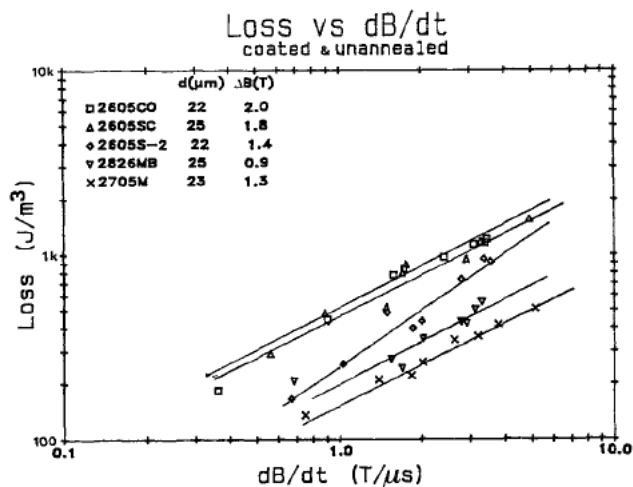


Figure 3. Losses as a function of dB/dt for several unannealed alloys.

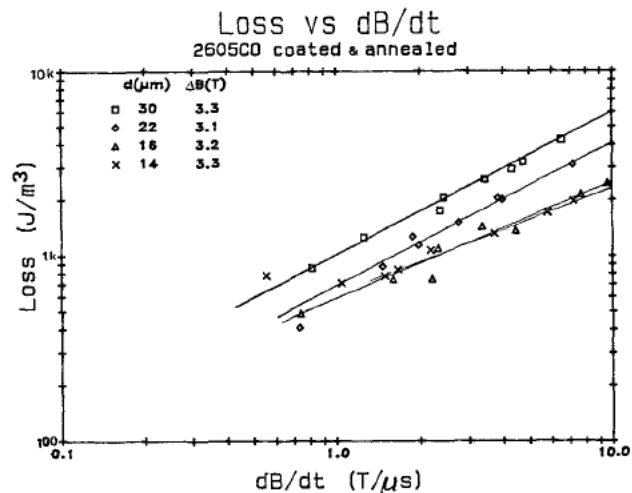


Figure 4. Losses as a function of dB/dt for several thickness ribbons of METGLAS Alloy 2605CO.

log scale have slopes of approximately 1.3 indicating that the losses are dependent on the thickness to the 1.3 power. Similar values of the exponent of t are obtained from graphs of average excess drive field vs dB/dt for the same toroids. Since slow, bar-domain magnetization predicts a t dependence and saturation wave domain magnetization predicts a t squared dependence, 10 T/ μs appears to be in the transition between these modes of magnetization. Other work on metallic glasses showed losses approaching t squared only for thicknesses greater than 40 μm at magnetization rates up to 3 T/ μs [5].

The ribbons of METGLAS Alloy 2605CO in Figure 4 with thickness closest to a nominal 25 μm show very similar behavior with respect to dB/dt. The slope of the lines yields an exponent of 0.75 to 0.85 for dB/dt. The thinnest ribbons, however, show a much lower slope. Their slope gives an exponent of 0.5. Since thinner ribbon requires higher dB/dt before achieving saturation wave-like behavior, it is not surprising that these thin ribbons have an exponent close to one half. Similar behavior is shown for METGLAS Alloy 2605SC in Figure 5. The thinnest ribbon has a dependence upon dB/dt to the 0.6 power. As discussed above, dependence of losses on the square root of dB/dt has been observed before in the transition region.

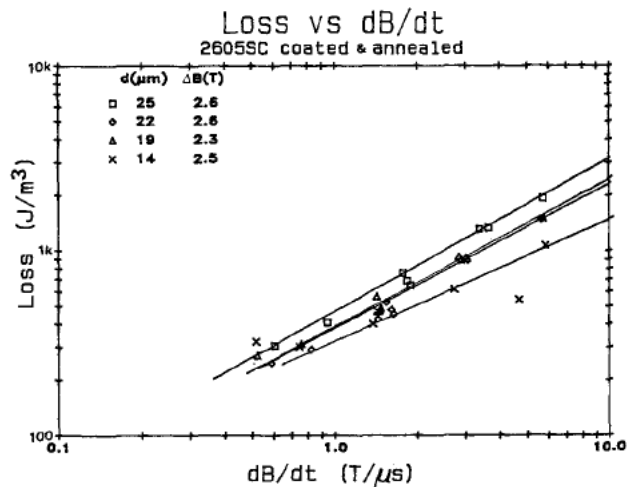


Figure 5. Losses as a function of dB/dt for several thickness ribbons of METGLAS Alloy 2605SC.

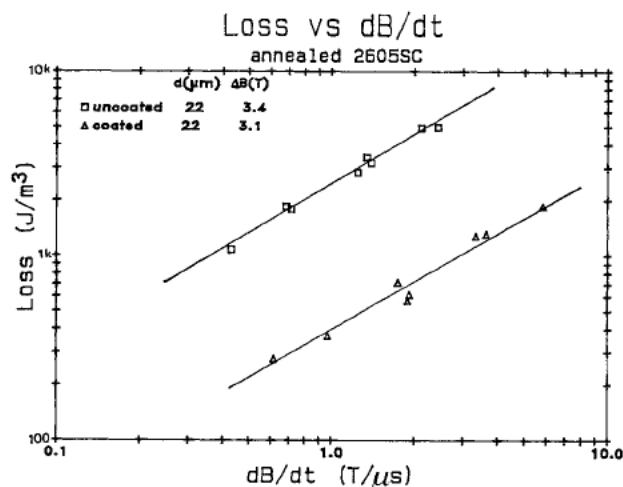


Figure 6. Losses as a function of dB/dt for annealed METGLAS Alloy 2605SC, both insulated and uninsulated.

The difference between insulated and uninsulated ribbon is shown in Figure 6 for METGLAS alloy 2605SC. The losses for uninsulated ribbon were 5 times those for the insulated ribbon. Large interlaminar eddy currents cause the extra losses. The interlaminar losses, of course, depend upon the surface of the ribbon. Insulation is often not necessary on metallic glass ribbon at low frequencies due to surface roughness and a slight naturally occurring surface coating. However, magnetizing 50 mm by 25 μm ribbon at 10 T/ μs will induce over 10 volts between adjacent layers. It was often noticed that for uninsulated ribbon, losses at lower dB/dt rates would increase when remeasured after measuring the toroid at the highest dB/dt. Whatever insulation had been present was permanently degraded.

Maximum pulse permeabilities are shown in Figure 7 for the ribbons of various alloys approximately 25 μm thick. The permeabilities were measured by calculating the maximum ratios of $\Delta B/H$ from dynamic magnetization curves. The permeabilities have been divided by $4\pi \times 10^{-7}$ to result in relative permeabilities. Despite the scatter in data for some of the alloys. The slope is approximately the reciprocal of the slopes in Figures 1 or 2.

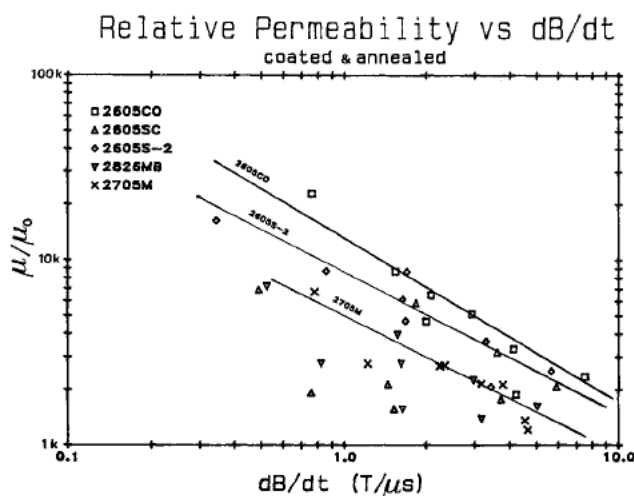


Figure 7. Maximum relative pulse permeability as a function of dB/dt for several alloys.

Conclusions

Measurements of losses and average drive field derived from dynamic magnetization measurements on several metallic glass alloys to 10 T/ μs have been reported. The exponent of the dB/dt dependence of these quantities is less than the value of one expected for saturation wave behavior. The thickness dependence of these quantities also has an exponent less than that for saturation wave behavior. However, with the exception of the thinnest ribbons, the dB/dt exponents are larger than the value of $1/2$ expected for bowed bar domains. Therefore, this regime is probably near the transition to saturation wave behavior. Measurements at higher dB/dt are necessary to resolve the issue.

References

- [1]. D. L. Birx, E. J. Lauer, L. L. Reginato, D. Rogers, Jr., M. W. Smith and T. Zimmerman, "Experiments in Magnetic Switching," *Proc. 3rd IEEE Int'l. Pulsed Power Conf.*, Albuquerque, NM, June 1981, p. 262.
- [2]. W. C. Nunnally, "Stripline Magnetic Modulators for Lasers and Accelerators," *Proc. 3rd IEEE Int'l Pulsed Power Conf.*, Albuquerque, NM, June 1981, p. 210.
- [3]. E. L. Neau, "COMET: A 6MV, 400kJ, Magnetically Switched Pulse Power Module," *Proc. 4th IEEE Int'l Pulsed Power Conf.*, Albuquerque, NM, June 1983, p. 246.
- [4]. C. H. Smith, "Metallic glasses in High-Energy, Pulsed-Power Systems," in *Glass...Current Issues*, (A. F. Wright and J. Dupuy eds.) Martinus Nijhoff, Dordrecht, Holland, 1985, p. 188.
- [5]. C. H. Smith, D. Nathasingh and H. H. Liebermann, "Thickness Dependence of Magnetic Losses in Amorphous FeSiC Ribbon under Step dB/dt Magnetization," *IEEE Trans. Magn. MAG-20*, 1320 (1984).
- [6]. R. C. O'Handley, "Domain Wall Kinetics in Soft Ferromagnetic Metallic Glasses," *J. Appl. Phys.* 46, 4996 (1975).
- [7]. R. M. Jones, A. J. Collins and N. G. Cleaver, "A Comparison of the Step dB/dt Pulse Magnetization Losses in Some Amorphous Ribbon and Conventional Toroids," *IEEE Trans. Mag. MAG-17*, 2707 (1981).
- [8]. R. M. Jones, "Step dB/dt Magnetization Losses in Toroidal Amorphous Ribbon and Polycrystalline Cores," *IEEE Trans. Mag. MAG-18*, 1559 (1982).
- [9]. P. Williams and J. E. L. Bishop, "Magnetic Domain Walls and Pulsed Magnetization Reversals in Amorphous Fe₄₀Ni₄₀P₁₄B₆ Ribbon under Tension," *agn. and Magn. Mat.* 20, 245 (1980).
- [10]. D. S. Rodbell and C. P. Bean, "Influence of Pulsed Magnetic Fields on the Reversal of Magnetization in Square-Loop Metallic Tapes," *J. Appl. Phys.* 26, 1318 (1955).
- [11]. R. W. DeBlois, "Domain Wall Motions in Metals," *J. Appl. Phys.* 29, 459 (1958).
- [12]. J. E. L. Bishop and P. Williams, "A Comparison of Rapid Surface and Volume Magnetization Measurements on 50% NiFe Tape with Models of Eddy-Current Limited Domain Wall Motion," *J. Phys. D: Appl. Phys.* 10, 225 (1977).
- [13]. S. D. Winter, R. W. Kuenning and G. G. Berg, "Pulse properties of Large 50-50 NiFe Tape Cores," *IEEE Trans. Magn. MAG-6*, 41 (1970).